Chapter

A Case Study on the Fire Safety in Historic Buildings in Slovakia

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Abstract

This chapter deals with the issue of fire safety in historic buildings that undergo functional change, restoration, replacement of construction, facade or installation renovation. It analyzes the current technical state in relation to microclimate and fire safety in historic buildings in Slovakia. It pays attention to the legislative framework for building conservation in the Slovak Republic considering its impact on the reconstruction and restoration of historic buildings. It assesses approaches and methods for fire safety solutions in historic buildings depending on the extent of their modification—intervention in the layout, function and construction. It presents solution procedures and knowledge in terms of application of fire safety requirements in historic buildings using model examples in accordance with the Slovak legislation.

Keywords: fire safety, restoration, historic buildings, legislation, model examples

1. Introduction

The successful restoration or renovation of a historic building depends on the integration of new operational requirements into the existing premises without the necessity of changing its original structure, layout and appearance. It is important for the building conservation to preserve the building's originality after its renovation and provide better microclimate and safety standard. The extent of the construction changes is connected with the extent of changes to fire safety solution. Restoration of a historic building can be defined as a set of layout and construction modifications implemented into the building structures in such a way that the building's original height and ground plan can be preserved. The construction interventions modify the building's technical parameters such as layout, load-bearing capacity, thermal and acoustic protection and fire safety. The building proceeding in the Slovak Republic related to the above-mentioned changes follows Act No. 50/1976 Coll. on town planning and building code.

Restoration of a historic building can be as follows: (a) an exact restoration, based on the detailed documentation of the building's original condition; (b) analogous restoration, based on the verifiable similarity or sameness with a better preserved building; and (c) hypothetical restoration, based on a substantiated, scientifically formulated hypothesis (assumption), giving the base for rebuilding a destroyed or disappeared building or its part.

Nowadays, most original historic buildings are not suitable for the occupation; they do not meet either hygiene or static, thermal and fire protection requirements. As for the restoration of a historic building, it is important to pay attention to the choice and optimization of building materials and the optimization of the building's functional use in terms of fire safety.

In these cases, the fire safety measures should be the result of a compromise among the fire protection, building conservation, building law and quality requirements for the building's new function. Fire safety in historic buildings is applied using passive and active fire protection of spaces and structures.

2. Analysis of the current fire safety in historic buildings in Slovakia

Based on the data from fire and rescue corps from 2013 to 2017, there are 2450 buildings of historic significance in Slovakia. Nowadays, the fire safety in historic buildings of great national and cultural importance (e.g. castles, cathedrals, mansions, etc.) where many rare museum exhibits are located is provided by electric fire signalization (EFS) equipment, fire extinguishers, internal and external fire cocks and firefighting measures applied in the building's operation. These measures are related to the fire training of employees who stay in the building during the operation. Each employee is trained how to eliminate fire in its initial phase, evacuate persons and exhibits and call the firefighters.

As stated in the Act of the Slovak Ministry of Interior No. 199/2009 on fire protection as amended, the building's operator is obliged to work up, keep and maintain the fire documentation according to the current condition and ensure it is respected. Each owner or administrator of a listed building should determine a qualified person who will be responsible for respecting all operational and organizational measures related to fire safety in a building and will keep and update the fire documentation. Trained persons provide and take regular prophylactic fire inspections of firefighting equipment.

Fire brigades regularly carry out training exercises in significant listed buildings to check their firefighting skills, means and methods and the accessibility of fire equipment in buildings. Despite the above measures, the real fire protection in most historic buildings in Slovakia is weak, and fire alarm systems are not located in all buildings. As Fire and Rescue Service Report 2018 states, there were 40 fires in such heritage buildings in the last 10 years. The most common cause was negligence, technical failure or deliberateness combined with the fire risk at the time of the building's operation.

Analysis of fire safety in listed buildings is primarily focused on firefighting equipment in terms of its location, availability and functionality as well as on staff readiness to use it effectively [1]. The most common deficiencies found during the fire inspections or in analyses of fire causes in such buildings are as follows:

- Missing or non-functional electrical fire alarm
- Non-functional hand fire extinguishers or their bad location in terms of accessibility at the time of fire
- Missing, capacity-insufficient or unmaintained fire hydrants
- Access roads badly rideable for the fire brigade due to insufficient road width and reinforcement or badly designed crossroads
- Employees inadequately trained for firefighting and missing fire documentation determining evacuation plans for employees, visitors or exhibits

- Insufficient maintenance of public spaces in terms of fire spread, location and storage of flammable materials in the immediate vicinity of the building

- Improper handling with the heat or ignition source, that is heaters, welding kits and handling with an open fire, where smoking is prohibited, etc.

- Technical defects in electrical installations or other equipment

- Incendiarism, vandalism

It is not always possible to prevent fire in a building despite the implementation of fire-protective and operational measures, especially in unforeseeable natural disasters. In general, if fire safety measures are kept at all levels of protection, it is supposed that the building does not collide with fire. If fire safety measures are missing, neglected or non-functional at the time of fire, it often causes big artistic and architectural losses.

Here is the example of fire in the castle of Krásna Hôrka from 2012. The fire progress is shown in **Figure 1b**. Fire was caused by children who carelessly handled free flame near the castle hill. They threw a burning object into dry grass that ignited. As there was strong wind, fire spread rapidly onto the combustible castle roofs covered by wooden shingles (see **Figure 1a**). The castle consists of three buildings. The original upper castle dates from the fourteenth century; the middle and lower castles were built later by the original owners. The castle housed a permanent display of period works of art giving basic information on the castle and its original owners. There were original exhibits with a high museum value. The original roof structure consisted of timber trusses covered with wooden shingles and took the area of about 5000 m^2. The lower and middle castle has vaulted ceilings; the upper castle has steel-bearing ceiling structure with a wooden flap. The castle has stone and brick external walls.

Fire safety in the castle before fire included passive fire protection, roof space had no accidental fire load, and timber truss members were treated with fire coating

Figure 1.
The castle of Krásna Hôrka before fire, during fire, after fire and at the present time. (a) Original castle timber roofs before fire in 2012; (b) fire in the castle in 2012; (c) the castle after fire in 2012; (d) the castle at the present time.

in 2000, and active fire protection—electric fire signalization—is installed in the roof space [2].

The Gothic tower contained a water reservoir of about 66 m^3; the upper castle contained fire-water hose systems and wall hydrants. Powder fire extinguishers were installed in all spaces. Although the castle was protected at the time of fire by both passive and active fire protection, its protection was not sufficient considering the outside source of fire, climatic conditions and burning rate of dried roof timber.

The fire lasted for about 3 days in terms of the quantity of timber structures and unfavorable natural conditions—strong wind. The roofs burned down (see **Figure 1c**). The firefighting was slowed down due to the road that was badly accessible for the fire brigade—there is only one access road leading to the castle. The water source was far from the burning area, and it was not possible to use the water reservoir in the castle.

The fire affected mainly the Gothic castle that was restored in 1982. The part of the ceiling fell down; some exhibits such as swords and other historical weapons were destroyed. The interior exhibits in the lower and middle castle and the Francis Museum survived without harm. Overall, 90% of all historic exhibits were saved. The castle building suffered fire damage especially on its construction, and the total damage was estimated at approx. 8.05 million €.

Nowadays, the castle's restoration is coming to an end. All roofs, including load-bearing and truss structures, were built as replicas of the original structures, taking into account the forms they had at the time of the last major castle's style alternation after fire in 1817 (1818). The original wooden shingle roof is replaced by burnt ceramic roofing, and the bastions have metal roofing (see **Figure 1d**). In this case, fire was caused by negligence and climatic conditions.

3. Past and contemporary legislative regulations for fire safety solutions in historic buildings in Slovakia

3.1 Legislative regulations in the past

No legislative standards were applied to the construction of buildings in terms of fire protection in the Middle Ages. The fire protection criteria in buildings with timber load-bearing structures were set out in the regulation issued probably by William I. Conqueror (1028–1087). All fireplaces in buildings were required to be put out at night and in the absence of persons. Furthermore, this regulation was supplemented by the requirement to cover the fireplace to prevent air access to the hot ash [24]. It is known from history that after the fire outbreak in the settlement, the consequences were global and fatal for inhabitants due to the combustible roofs and limited possibilities of firefighting at the time. For this reason, the past legislation focused on the fire protection in buildings due to the high risk of easy and rapid fire spreading from building to building.

The oldest legislation valid in our territory for the royal free cities, as well as the towns and villages of higher importance with an authorized municipal office that deserved to be added to the royal free cities, was "Fire Regulations for the Kingdom of Hungary" issued in Presburg in 1788. This regulation was divided into four chapters:

1. How to prevent the occurrence of fire—related to the rules for construction of chimneys and internal fireplaces

2. How to detect fire early if it occurs—signals generated by bells

3. How to extinguish fire as quickly as possible—each settlement was obliged to have a public water reservoir, pond, lime trees planted on four sides of neighboring farm houses, etc.

4. How to prevent harmful consequences that may occur after fire

Growth in the manufacturing sector in the late nineteenth century brings the use of technique for firefighting. Fire protection starts to be provided by professional fire brigades. Non-combustible building materials—reinforced concrete, burnt ceramic blocks, etc.—are used for the construction of buildings that have natural protection against fire spreading within the building as well as from one building to another. The timber load-bearing elements of ceilings were protected by plasters and embankments made of non-combustible materials. Wooden shingles, straw and reed on the roofs were replaced by ceramic roofing. The timber trusses were separated from chimneys and treated with fire-resistant coatings to reduce their flammability. There was no fire risk in the roof spaces with trusses; they were separated from vertical shafts.

3.2 Contemporary legislative regulations for fire safety solutions in historic buildings in Slovakia

The obligatory regulation for fire protection currently valid in Slovakia is Act No. 314/2001 as amended and implementary regulation issued by the Slovak Ministry of the Interior No. 121/2002 Coll. on fire prevention, as amended. The implementary regulation No. 94/2004 as amended specifies requirements for the project solution. The restoration of historic buildings takes into account mainly all society's requirements for the preservation of their original appearance and material solutions considering adequate fire safety. Legislation valid for the restoration of historic buildings in Slovakia is Act No. 49/2002 on the heritage protection as amended, issued by the Slovak National Council and followed by the implementary regulations. Details on the performance of monument research are specified in the implementary regulation No. 253/2010 Coll. issued by the Slovak Ministry of Culture. It determines, based on monumental survey, the conditions for methods and extent that can be used in the remediation of existing historic buildings. Survey conclusions are one of the bases for the design and extent of construction work as well as the choice of materials used in the renovation. The requirements and conditions for the restoration of historic buildings in terms of fire safety are limited due to the specific conditions. The restoration and renovation of buildings in Slovakia follows the criteria specified in Slovak Standard STN 730834 on construction changes.

In terms of fire safety, the building's alternation is the only alternation resulting in a higher fire risk, number of persons, replacement of load-bearing structures and installations within the affected spaces. The extent of fire safety measures is determined by the extent of changes in the building's construction or operation [15]. The alternations of buildings can be divided into three categories:

The **first category** includes alternations without the functional change resulting in the higher fire risk. There are only minor repairs to the original structures done without changing their reaction to fire and modernization of installation systems in buildings.

The **second category** includes alternations to the functional use of the building's part or the entire building that will change the fire risk, fire resistance requirements for the fire-separating structures, number of people and related evacuation plan. Such alternations to the buildings are related to the fire compartmentation, fire protection, changes in ventilation system, fire separation of evacuation routes and requirements for the installation of firefighting equipment.

The **third category** includes restorations of buildings, changing the use, useful area and fire height. This is related to the buildings where more than 50% of the total floor area in the fire section changed is found in the building's extension or superstructure [1]. In such cases, the fire safety measures are required to be done completely as in the new buildings, and their assessment is also in accordance with the legislation applicable to the new buildings.

The building's functional change often brings the exchange of a building's owner or manager whose criteria for the heat-moisture regime in the indoor environment are higher. As a result of this change, there is a requirement to increase building's thermal protection if the building conservationists give the permit. Thermal protection in historic buildings is done at least to eliminate microclimate deficiencies, optimally considering the building's energy efficiency and sustainability in terms of its environmental impact [3].

If listed buildings are restored, the fire safety solution must contain an expert opinion analyzing the specific building's conditions and determining requirements for its fire safety depending on the boundary conditions such as functional use, design, layout in the vertical direction, occupancy, number and quality of emergency routes, availability of access roads and firefighting water. The fire safety solution should take into account at least the following requirements: the operations with the high fire load and fire factor higher than 1.1, except theaters, exhibition halls, museums and areas for visitors, cannot be situated in the listed buildings whose original function of spaces is modified.

The fire alarm systems are required to be installed in the unique historic spaces, e.g. spaces containing murals, unique historic collections, unique structures or elements made of flammable materials.

The fire safety reassessment is required to be done if alternations to historic buildings result in their restoration or renewal.

4. Theoretical analysis of physical, design and layout determinants affecting the restoration of historic buildings in terms of fire safety

Historic buildings were usually constructed using a combination of combustible and non-combustible materials. The most used building material was wood—in roof structures, ceilings and stairs. It was used in the past as a single building material to construct buildings of folk architecture in Slovakia. Historic buildings usually contain composite construction systems. The cellars and basements had stone or masonry walls, and ceilings had ceramic vaults. The above-ground floors had peripheral walls that were built using a combination of non-combustible masonry made of burnt and non-burnt bricks or stone and combustible wood-beamed ceilings. The ceilings were either visible or covered with plaster usually applied to the reed mats. Roof load-bearing structures contained roof trusses with wooden purlins statically independent on the last floor ceiling. Depending on the building's ground plan dimensions, the purlin or collar systems were mostly used for small spans in folk architecture; a combination of standing saddles and hanging trusses or strut frames was used for larger spans, e.g. mansions, castles or churches.

The roof space was usually naturally ventilated and had no functional use. The attic was accessible via wooden or stone single or spiral stairs due to the repairs and maintenance. The wooden ceilings and trusses as well as the dimensions of their members were based primarily on the spans they covered and empirical and technical possibilities of the builders at the time of construction. Due to the technical possibilities of the joints affecting the load-bearing capacity of the purlin system, the wooden members were dimensioned with a significant static reserve. The wooden members were usually joined by mortising or lapping, and their fire resistance was achieved by partial walling [4].

The fire safety degree is determined on the basis of fire load density with dependence on the ventilation parameter, fire risk, building's fire height and combustibility of used building elements according to Table 8 STN 730802/10. The degree of fire safety in building structures (DFSB) value is the basis for determining fire safety requirements of load-bearing and fire-separating structures given in Table 12 STN 730802/10. These requirements are compared to the current fire resistance of the existing structures.

The fire resistance of the original structures can be taken from the table in STN 730821 or calculated according to Eurocodes depending on their static stress.

4.1 Fire resistance of load-bearing and fire-separating structures

Fire resistance is the ability of building structures to withstand the effect of fire. It is defined by the time during which the structures can be exposed to fire without damaging their function. The fire structures can be divided into load-bearing and non-load-bearing, in terms of their function, and fire-separating or interior load-bearing, in terms of their location in a fire compartment. If the fire-separating structure is load-bearing and located at the frontier between fire compartments, it must meet the criteria of load-bearing capacity (R), integrity (E) and thermal insulation (I) at the time of fire. If the load-bearing structure within the fire compartment is a post, it must meet the R criterion at the required time. The stability of fire structures along the building's height must not depend on the stability of structures with lower fire resistance on lower floors. The fire resistance of fire-separating structures is determined by a test or calculation. The design and assessment of fire resistance of building structures follow a set of standards—Eurocodes EN 1991-1-2, EN 1992-1-2, EN 1993-1-2, EN 1994-1-2, EN 1995-1-2, EN 1996-1-2 and EN 1999-1-2.

The fire resistance of building structures is calculated using the design procedure in terms of the requirement for the result accuracy and specific boundary conditions of a fire compartment. First, thermal analysis of a fire compartment is done, then the heat transfer into the structure and temperature development within the structure is determined, and finally the fire-separating structure is analyzed. Detailed analyses of the temperature in a fire compartment are determined by dynamic simulations and end-element methods. Simpler procedures are used to determine the temperature in a fire compartment by parametric temperature curves or nominal temperature curves. The resulting fire resistance determined according to the nominal standard curves is the standard fire resistance (**Figure 2**).

The heat transfer within the structure for detailed solutions is determined by the end-element method; for less detailed solutions, it is determined by incremental or direct methods. Direct methods used for heat transfer are conservative and valid only to a limited extent and can be used to assess only particular elements of a fire-separating structure. The calculation is based on room temperature [18–20]. Fire resistance verification of a fire-separating structure can be done by the three following views:

Time—clearly expresses the reliability reserves of the structural element:

$$t_{fi,d} \geq t_{fi,requ} \tag{1}$$

where $t_{fi,d}$ is the design time of fire resistance and $t_{fi,requ}$ is the required time of fire resistance.

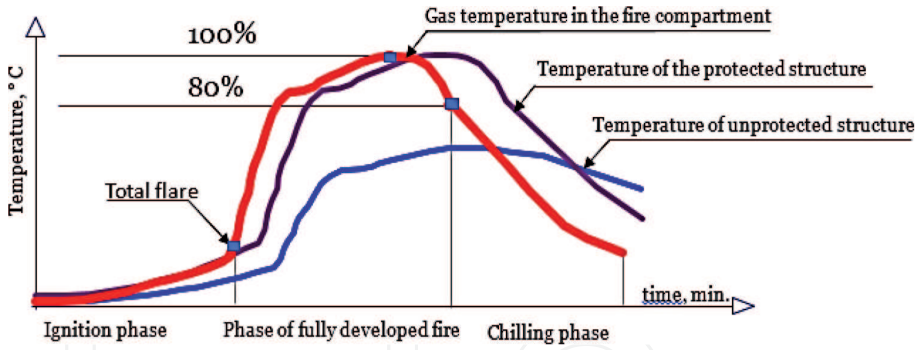

Figure 2.
Surface temperature on fire-separating structures without surface fire protection and with fire-protective lining during standard fire [6].

Load-bearing capacity—the easiest in terms of calculation because the method is similar to the assessment at the room temperature:

$$R_{fi,d,t} \geq E_{fi,d,t} \tag{2}$$

$R_{fi,d,t}$ is the design value of load-bearing capacity of a member in fire during the time t and $E_{fi,d,t}$ is the design value of fire load effects during the time t.

Temperature:

$$\theta_d \geq \theta_{cr,d} \tag{3}$$

where θ_d is the design value of material temperature and $\theta_{cr,d}$ is the design value of critical material temperature.

Simplified assessment of structural elements in terms of their fire resistance is given in tables in STN 730821: 1973, which is currently valid for the assessment of building structures during construction changes. The fire resistance values of building structures are given in particular tables considering building materials and static load of the structures—walls, columns and ceilings [5].

4.2 Fire resistance assessment of existing fire-separating structures in a model solution

The following model example shows a fire safety solution used in the restoration of a folk house situated in the village of Vel'ké Leváre. The folk house is dated to the Hutterian culture period. It was restored with the intention of preserving its original layout including the original constructions and elements. The building has a combined structural system—the brick external walls, wooden beam ceiling and collar beam truss. It was necessary to optimize the boundary conditions of the given solution so that the consequences of a functional change regarding the current constructions could be minimal. The museum display showing the original culture was situated in the restored space after the original supporting elements, roof covering and original wall and floor surfaces had been replaced or repaired. The external wall is combined stone with bricks. There are wooden ceilings with visible beams supported by a wooden beam. This beam is embedded into the perimeter walls, and its center is supported by a column. The wooden truss has a two-level collar beam.

The building's functional use was changed in terms of fire safety—it became a museum, that is its original residential function was changed into an exhibition one. The fire load increased but only on the first floor. The required value of the fire safety degree was not changed compared to the original one. The attic spaces used as living rooms serve today only to show the original truss construction. Considering the fire height of 0 m and the combined building's construction, the required fire safety degree is I, that is the same as in the original functional use.

The fire resistance requirement for the original load-bearing and fire-separating structures was not changed after the functional change of the restored spaces. The fire resistance requirement for the load-bearing ceiling members and perimeter wall is given according to STN 73082 and is dependent on the average fire load, that is the sum of the accidental and permanent fire load, coefficients of ventilation, flammability factor and use and type of firefighting equipment. In terms of the calculated fire load pv = 66 kg/m^2, the fire resistance requirement for the fire-separated structures is REI 30 (building envelope and roof), and the fire resistance requirement for load-bearing structures of a non-compact ceiling in an assessed fire compartment is R 30.

4.3 Fire resistance of the external wall in a model solution

The external wall is made of stone and brick and has a variable thickness of 530–630 mm. The required fire resistance for this model solution is REI 30 min.

In accordance with the values given in Table 1A STN 730821, the real fire resistance of the perimeter wall is well above the required value (**Table 1**).

As the dimensions of the assessed wooden ceiling members and column in a model solution are different from the members given in the standard, their real fire resistance is calculated according to EN 1996-1-2: 2004 Eurocode 6: Design of masonry structures, Section 1.2 general rules—fire resistance design of masonry structures.

In specific cases, the fire resistance of fire-separating structures can be determined by a calculation according to EN 1996-1-2: 2004 Eurocode 6: Design of masonry structures, Section 1.2 general rules—fire resistance design of masonry structures.

4.4 Fire resistance of the wooden ceiling in a model solution

There is a wooden beamed ceiling above the ground plan in the model example. The ceiling material and structure are visible (see **Figure 3**).

The ceiling beams are supported by a wooden beam. The wooden beam is fastened on the load-bearing peripheral walls and supported by a wooden column (see **Figure 4**).

The real fire resistance for load-bearing and fire-separating structures was calculated according to the methodology given in STN EN 1991-1-2: 2004; the

Type of a structural member	Thickness [mm]	Fire resistance REI
Masonry walls made of solid bricks perforated up to 15% of the volume, built on mortar of 4-CSN 2430 class, loaded and non-loaded with double-sided plaster	>180	240
Wooden beams loaded in bending, unprotected from three sides	140/200	40
Unprotected wooden columns loaded in buckling at λ = 75, see CSN 731701	200/200	20

Table 1.
Fire resistance of the fire-separating structures according to STN 730821 [17].

fire resistance of wooden members was calculated according to STN EN 1995-1-2 (Eurocode 5) depending on their mechanical stress [21, 22].

The real fire resistance for load-bearing and fire-separating structures is primarily dependent on their mechanical load during fire and fire load density caused by building's operation. Determination of fire resistance for structures in a fire compartment depends on the typical fire load density per unit of floor area (qf, d), burning rate coefficient, fire risk coefficients and fire protection coefficients. Estimated fire duration in the assessed fire compartment is determined after considering the influence of structures, ventilation and active firefighting equipment.

The fire resistance of wooden members affected by fire (wooden beam ceiling, column and girder) was specified using the effective cross-section method [7]. The methodology is based on the assumption that the first phase of burning wooden elements causes the surface burning and forms a carbonized layer. Such element becomes partially thermo-insulated by further thermal stress, which prolongs its fire resistance. The charring thickness is determined by the fire duration to which the element is exposed and by the charring rate. This interface or the location of the carbonized line in most coniferous and deciduous trees corresponds to the isothermal position of 300°C. After obtaining an effective cross-section, the element is assessed according to [8]. The method of reduced properties works with the residual cross-section (obtained after reading the carbonized layer) taking into account the changed strength and stiffness material properties based on the modified coefficient. In light of this assessment, all wooden load-bearing members in the assessed fire section of the museum met the required fire resistance without additional structural modifications.

The assessment of ceiling supporting members in terms of static load at a room temperature is given in **Table 2**. **Table 3** gives the assessment of supporting ceiling members in terms of static and fire load during a standard fire [23].

For material characteristics the following are considered: k_{fi}, coefficient of solid timber, k_{fi} = 1.25; $k_{mod,fi}$, modification factor for fire, $k_{mod,fi}$ = 1.0; and $\gamma_{M,fi}$, partial factor for timber in fire, $\gamma_{M,fi}$ = 1.0. For the calculation of charring depth, the following are considered: β_n, notional design charring rate under standard fire exposure, β_n = 0.8 mm/min (for solid timber); k_0, coefficient for non-protected

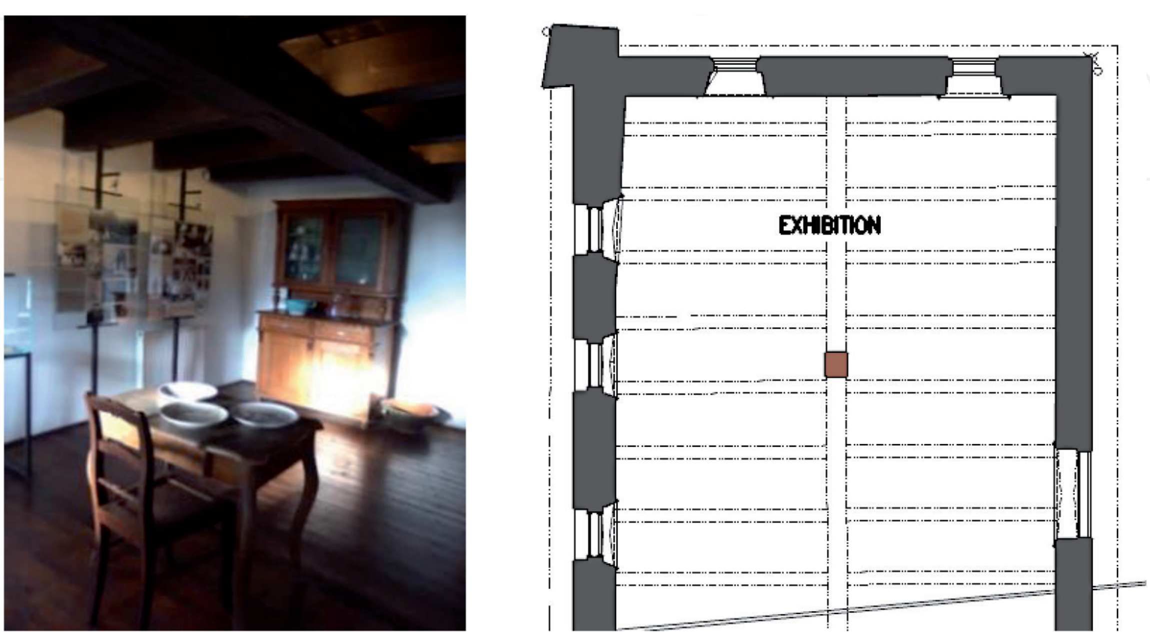

Figure 3.
Layout and visible ceiling in a model solution (left) and ground plan with assessed wooden truss (right).

Figure 4.
Supporting using a wooden beam and column (left) and ceiling wooden beam with a wooden decking (right).

No	Member	b [mm]	h [mm]	$M_{y,Ed}$ [kNm]	$M_{z,Ed}$ [kNm]	N_{Ed}[1] [kN]	ηfi [-]
1	Ceiling beam	200	250	6.35	0.63	0.53	0.6
2	Roof girder	300	270	14.64	−0.16	15.8	0.6
3	Column	d = 230[2]		0.11	1.30	55.50	0.6

where: ηfi—reducing factor for combined load. As simplification it is possible to use the value 0.6 (according to STN EN 1995-1-2).
[1]Positive sign (+) means tensile force; negative sign (−) means compression force.
[2]The average column diameter at its narrowest spot.

Table 2.
Parameters of static load of wooden ceiling supporting members at the room temperature.

surfaces, k_0 = 1.0; and d_0, layer thickness with assumed zero strength and stiffness, d_0 = 7 mm.

The structures assessed in terms of table values given in STN 730821 (see **Tables 3** and **5**) as well as values determined by a calculation in dependence on the current boundary conditions—static load and material characteristics of wood—meet the required fire resistance value [8].

5. Solution methods

If the restoration of listed buildings is designed, its preparatory phase analyzes the current fire risk in the building. The fire risk analysis examines the current fire risk and the extent of fire-technical and organizational measures [3].

5.1 Analysis of fire risk

The fire risk assessment can be divided into four phases:

Analysis of the current building solution in terms of fire safety—includes assessment of current or planned layouts, flammability of structures and materials, number of

No	Member	b [mm]	h [mm]	$M_{y,Ed,fi}$ [kN]	$M_{z,Ed.fi}$ [kNm]	$N_{Ed,fi}$ [kN]	$\sigma_{m,y,d,fi}$ [MPa]	$\sigma_{m,z,d,fi}$ [MPa]	$\sigma_{c(t),0,d,fi}$ [MPa]	Assessment bend + pressure (bend + tension)
						R30				
1	Ceiling beam	200	250	3.81	0.38	0.32	3.454	0.544	0.011	0.15 < 1.0 meets
2	Roof girder	300	270	8.78	−0.10	9.05	5.118	0.050	0.180	0.23 < 1.0 meets
3	Column	d = 230[2]		0.07	0.78	33.30	0.142	1.676	1.502	0.16 < 1.0 meets

[1]*Positive sign (+) means tensile force; negative sign (−) means compression force.*
[2]*The average column diameter at its narrowest spot.*

Table 3.
Parameters of static load of wooden ceiling supporting members at the standard fire temperature.

Densities in mega-joules per square meter					Pn conversion from EK (16,75) 80% fractile	Pn value from Table A1 in STN 730802
Occupancy	Mean (MJ/m²)	Percent fractile*				
		80	90	95		
Dwellings	780	870	920	970	52	40
Hospitals	230	350	440	520	21	20
Hotel rooms	310	400	460	510	24	30
Offices	420	570	670	760	34	40
Shops	600	900	1100	1300	54	90
Museums	300	470	590	720	28	60
Libraries	1500	2250	2550	---	134	120
Schools	285	360	410	450	22	25

Conversion factors: 1 MJ ≈ 0.948 BTU, 1 m^2 ≈ 10.8 ft^2.
**The percent fractile is the value that is not exceeded in that percent of the rooms or occupancies.*

Table 4.
Comparison of the fire load density values in different occupancies according to the data given in EN 1991-1-2 and Table A1 STN 730802.

staircases and their location in relation to the center of gravity of evacuated persons, ventilation of staircases and disposition possibilities of their fire separation, evacuate conditions for person and historic articles depending on the building's functional use in fire as well as the accessibility and safety of staircases for firefighters. It also assesses the possibilities of fire spreading in the building's open spaces, e.g. central representative staircases, open galleries, internal atriums, unsealed crawl spaces in ceilings, etc. The analysis determines the construction and division of the building into smaller units—fire compartments, location of fire doors and the way of their closing and risk of fire spreading to adjacent buildings.

Analysis of the current operational solution in terms of fire prevention—includes an assessment of the building's functional use considering the accidental fire load with regard to the fire resistance of the existing load-bearing structures and the number of persons in terms of the capacity of existing evacuation routes. It also contains assessment of internal organizational measures that should minimize the causes of fire such as regular inspections of electrical installations and appliances, technical equipment, chimneys, etc.

Analysis of the current fire detection system—includes an assessment of the function and location of the automatic fire detection system. If there is no such system installed in the building (this is the common situation in historic buildings in Slovakia), it is necessary to verify the organizational measures ensuring fire detection, that is to ask authorized employees to be helpful and use their senses. This includes regular inspections in the building by its guard. If there is no guard in the smaller buildings, the inspection is done by authorized employees at the end of working hours.

Analysis of the fire equipment availability in case of fire—finds out the location of portable fire extinguishers, their capacity and extinguishing agent. It analyzes the availability of internal firefighting water and wall fire hydrants as well as their position and functionality. It also verifies the location, capacity and functionality of external firefighting water sources, that is external hydrants, water tanks and natural water sources that can be used by fire brigades. It analyzes organizational measures related to fire extinguishing such as staff training, firefighting documentation, identification of emergency routes and access roads. After determining the

Original functional use of buildings, fire height	Functional usability	Fire hazard		DFSB STN 730802	Requirements for fire-separating structures in the composite construction unit on the first/last floor			
		a	pv (kg/m^2)		Walls	Ceilings	Roof	Fire dampers
					REI	REI	REI	EI, EW
Churches, fh = 0 m	Galleries	1.2	18	I.	30/15	30/15	15	30/15
	Museums	1.1	66	I.	30/15	30/15	15	30/15
	Concert halls	1.1	33	I.	30/15	30/15	15	30/15
Cloister premises, fh ≤ 9 m	Libraries	0.7	84	IV.	90/60	90/60	60	60/D1
	Coffee bars	1.2	37	III.	60/45	60/45	45	45/30
	Accommodation, apartment buildings	1.0	40	III.	60/45	60/45	45	45/30
	Administration	1.0	40	III.	60/45	60/45	45	45/30
	Education	0.9	22	II.	45/30	45/30	30	30/30
	Gallery	1.2	18	II.	45/30	45/30	30	30/30
	Museums	1.1	66	III.	60/45	60/45	45	45/30
	Hotels	1.0	30	III.	60/45	60/45	45	45/30
Castles, mansions, fh ≤ 12 m	Galleries, museums	1.1	66	III.	60/45	60/45	45	45/30
	Hotels	1.0	30	III.	60/45	60/45	45	45/30
	Club spaces	1.1	33	III.	60/45	60/45	45	45/30
Townhouses, villas, palaces, fh ≤ 12 m	Kindergartens	0.9	32	III.	60/45	60/45	15	45/30
	Hotels, apartment buildings	1.0	30	III.	60/45	60/45	45	45/30
	Administration	1.0	40	III.	60/45	60/45	45	45/30

fh—building's fire height; pv—calculated fire load in kg/m^2 (the average fire load value of the entire fire compartment); a—coefficient of combustible materials (burning rate) (Table A1 STN 730802); b—coefficient of ventilation efficiency (ventilation rate); REI—time in minutes (minimal time during which the criteria for load, stability and integrity of thermal insulation are met); EI—time in minutes (minimal time during which the criteria for integrity of thermal insulation are met); EW—time in minutes (minimal time during which the criteria for insulation integrity guided by radiation are met); DFSB—degree of fire safety of building structures (expresses the summary of technical requirements for fire-separating structures).

Table 5.
Optimization of functional changes in historic buildings in terms of fire protection requirements for original structural elements according to STN 73 0802/2010 and 2015.

current fire safety measures in the building, the restoration or functional change is optimized in such a way that the planned alternation would not reduce the current building's fire safety.

5.2 Fire safety design

The fire safety in buildings is generally a combination of passive and active measures ensuring the following points for each fire section during the fire:

- Retain the carrying capacity and stability of load-bearing structures and firefighting partitions at the required time.
- Reduce the development and spread of fire and smoke within the building.
- Reduce the spread of fire toward the surrounding buildings through windows, roofs and burning other structures.
- Enable safe evacuation of persons from the building.
- Enable effective and safe intervention of fire brigades.

The building solution for a historic building whose original function is planned to be changed contains mostly:

- Fire compartmentation of the building excluding concentrated fire load and reducing the open layouts going through more floors
- Detection of the fire risk resulting from the building's operation
- Fire resistance assessment of existing fire separation structures considering the fire risk, fire height and combustibility of load-bearing and fire separation structures including the possible solution for their additional fire protection
- Construction of protected emergency routes if it is possible; if not, it is necessary to reduce the building's occupancy
- Ensuring the accessibility of sufficient source of firefighting water and hand fire extinguishers
- Construction of the safe intervention routes including access roads and boarding areas

If there are some barriers on the access roads to the building such as castle hills or impassable entrance gates, it is necessary to determine a set of construction and fire-technical measures using active elements of fire protection, e.g. stationary fire extinguishing equipment.

5.3 Fire compartmentation

If it is possible in terms of building's operation, it should always be divided into several smaller fire compartments to minimize fire damage and increase the occupants' safety during evacuation and fire intervention. If there are no complications during the fire intervention and the fire brigade arrive in the first phase of fire, then there is minor material damage found usually in the fire-affected part of the building.

The separate fire compartments always include emergency routes, gathering areas, rooms with a high fire load, warehouses and technical rooms.

The fire separation of an existing staircase from adjacent spaces with vertical fire load divides the building into more floors that are simultaneously fire compartments. They reduce the spread of thermal radiation and smoke within the building and relatively safe evacuation [9]. The staircases are separate fire compartments without fire risk; their layout, ventilation and air exchange frequency depend on the time required for evacuation of persons.

The separate fire compartments should be all spaces with installations—air-conditioning engine rooms, boiler rooms, switch rooms, installation shafts as well as storage areas, deposits, etc.

If the spaces are modified for housing, accommodation, hospital or meeting, they must be divided into the fire compartments. Each dwelling unit must be a separate fire compartment; the same is valid for bed sections in hospital, hotel rooms or meeting rooms and museums, exhibition halls, theaters, etc. Any room or fire compartment containing more than 200 people is considered to be a meeting room. There are no exceptions allowed, and it is always necessary to reach an agreement between the fire safety requirements and building conservation.

The multistory fire sections require higher fire resistance of building structures than single-story ones, as the fire load is concentrated on the first floor. If fire occurs, it is supposed that the entire building will burn at the same time. The building structures are required to withstand thermal stress without breaking their stability and integrity throughout the fire of the entire building, that is longer than the single-story fire compartment. Finance that are saved by reducing the fire-separating structures such as doors, ceilings, etc. are usually used to ensure the fire resistance of the existing structures if they are composite and combustible. Such solutions absolutely do not respect property protection and safety of persons in the building. If fire damage is to be minimized, the building must be divided into fire compartments. The maximum area of fire compartments depends on the combustibility of the structure, number of floors and coefficient of combustible substances.

5.4 Fire risk

The fire safety solution in historic buildings whose original function is changed depends on the extent of construction modifications and planned functional use of the original spaces. If the functional use of historic buildings is planned to be changed, the real fire risk related to the planned operation should be taken into account. The fire risk is specified for each fire compartment. Its value depends on the combustibility and heating capacity of materials used in particular spaces depending on their functional use, coefficient of combustible substances, ventilation and active fire safety equipment. It is calculated from the relation:

$$qf, d = qf, k.m.\delta q1\ \delta q2\ \delta n\ \mathrm{MJ/m^2} \tag{4}$$

where qf, k is the fire load density per floor area unit $\mathrm{MJ/m^2}$; m is the burning rate coefficient; δq1 is the fire danger; δq2 is the fire danger; and δqn is the function of active fire-protective measures (δqn1–δqn2 automatic fire extinguishers, δqn3–δqn5 automatic fire alarms).

The fire load density expresses the probable fire intensity in the fire compartment or its part.

5.5 Fire load

Fire load can be determined by a calculation from relation (5) or from statistical values; examples for selected types of operations are given in **Table 1** (source EN 1991-1-2 and comparison with parameters STN 920201-1).

Fire load Q in a fire compartment is defined as the total energy that can be released in fire occurrence. One part of the total energy will be used to heat the space (walls and internal gas); the rest of the energy will be released through openings—building elements such as wall and ceiling linings. The building content such as furniture is the fire load. Fire load Q divided by the floor area gives the fire load density qf. Typical fire load density in EC 1 is defined by the equation [6]:

$$\mathrm{qf,k} = \frac{1}{Af} \cdot \sum_{i}^{\infty} (\psi i \,.\, mi \,.\, Hui \,.\, Mi) \tag{5}$$

where Mi is the mass of material i [kg]; Hui is the net heating value of material i [MJ/kg]; mi is the factor describing combustible properties of material i; Ψi is the factor assessing protected fire load of material i; and Af is the floor area of the fire compartment [m^2].

HuiMi represents the total amount of energy that is contained in material i and released if combustion process is complete. Factor "m" is a non-dimensional factor between 0 and 1 representing combustion efficiency: m = 1 corresponds to complete combustion, and m = 0 if materials do not contribute to fire. The value of m = 0.8 is suggested for standard materials; the value of Hu = 17.5 MJ/kg is suggested for wood, resulting in 14 MJ/kg for (m.Hu).

Common building designs supposing the use of similar material quantities with the same heating capacity in installations can work with the statistical value of typical fire load density, as defined in EN 1991-1-2; if the designs are done in Slovakia, they follow Table A1 STN 730802. The value of accidental fire load stated in this standard is the weight of wood in kg calculated per unit of the floor area of fire compartment in m^2, whose heating capacity is the same as heating capacity of all combustible materials in this area. **Table 4** shows the data comparison.

The functional change of the original spaces changes the fire risk and number of persons. The change of building's fire height, e.g. by roof extension, changes the original building's fire height, fire protection requirements and evacuation plans. An increasing number of persons in the building change the requirements for the capacity and ventilation of emergency routes as well as the fire resistance of fire separation structures. Therefore, it is very important for the investment plan (as for space function and useful floor area extension) to be optimized in such a way that the original boundary conditions would not be changed fundamentally in terms of fire safety and would not require additional significant alternations to the building structures affecting their historic value.

The fire resistance requirements for building constructions specified in STN 73 0802 are directly dependent on calculated fire load, building's fire height and combustibility of constructions used in a building. It is optimal to prefer operations with a calculated fire load up to 50 kg/m^2 if the function of restored buildings containing mostly composite construction systems was changed. This value considers the operational fire load, surface finishes, effect of ventilation and fire-technical equipment. Classrooms, hotel rooms, coffee bars, offices or galleries are classified as spaces with medium fire load (medium fire development) (see **Table 5**).

Calculated fire load is determined by the relations:

$$\mathrm{pv} = (\mathrm{pn} + \mathrm{ps}).\mathrm{a.b.c}\ \left(\mathrm{kg/m^2}\right) \tag{6}$$

which depends on: pn—accidental fire load from furnishings given in Table A1 STN 730802 [16]; ps—stable fire load from windows, doors, floor and wall coverings given in Table A1 STN 730802; and a—coefficient of combustible materials (burning rate),

$$a = (an.pn + a.ps)/pn + ps \tag{7}$$

where an is given in Table A1 STN 730802, as is 0.9 and b is the coefficient of ventilation efficiency (ventilation rate),

$$b = S.k/So.\sqrt{ho} \tag{8}$$

where S is the floor area of fire compartment; So is the total window area in fire compartment; ho is the average window height in fire compartment; k is the coefficient determined according to Section 4.5.4. STN 730802; and c is the factor of fire safety equipment efficiency,

$$c = c1.c2.c3.c4 \tag{9}$$

where c1 is the coefficient of fire detection (see **Table 2** STN 730802); c2 is the coefficient of fire brigade intervention (see **Tables 3** and **4** STN 730802); c3 is the coefficient of fixed fire extinguishing system (see **Table 5** STN 730802); and c4 is the coefficient of automatic fire sprinklers (see Table 6 STN 730802)

Table 5 gives the calculated fire load of a typical fire compartment considering the most common use of space in historic buildings whose function was changed during their use. Model examples considered medium ventilation effect with the coefficient value b = 1. As the most historic buildings do not contain active fire safety equipment, all calculations considered the coefficient value c = 1. Subsequently, DFSB is determined depending on the calculated fire load value, combustibility of structures in the fire compartment and the building's fire height (see Table 8 STN 730802). DFSB expresses the summary of technical requirements for fire-separating structures; required minimum fire resistances of fire-separating structures are taken from Table 12 STN 730802.

If building conservation and finance costs are taken into account, it is not possible to carry out every functional change in listed buildings. The building can be classified as unsuitable if fire safety cannot be ensured with reasonable economic and operational costs. The new functional use must not reduce the existing fire safety. In general, listed buildings renovated by using only technical solutions cannot have any functional use. It is optimal for listed buildings to have as low fire risk as possible in terms of fire safety and subsequent fire safety measures [10].

6. Evacuation

People evacuated from a burning building are endangered by toxic gases released during combustion, flame, high temperature, smoke and lack of oxygen. The safe evacuation depends on the building's division into fire compartments using fire-separating structures. Their design is based on the assumption that fire will occur in a fire compartment so people present in other fire compartments will not be exposed to fire. The building's division into fire compartments is done in such a way that the life and health loss would be minimal or none. Fire-separating structures in fire compartments should prevent fire and its products from spreading. Separate fire compartments always form protected emergency routes.

Fire compartmentation in historic buildings is often limited due to the building conservation. This fact has a major impact on the safe evacuation. Open staircases, galleries and non-solid ceiling structures help fire spreading within such buildings. Thermal radiation, toxic gases and smoke are spread throughout the building. The fire intensity and time are increased by combustible materials in built-in ceilings, columns, staircases, wall facings and insulations of technical installations. This affects the safety and speed of people's movement within the affected fire compartment on unprotected emergency routes.

Safety and fluency of evacuation in historic buildings with original layout and functional use is often limited by:

- Open staircases—unprotected emergency routes with limited evacuation time and no other evacuation staircase

- Partially protected existing narrow spiral or ladder stairs limiting the speed of people's movement that can be used by a limited number of persons during evacuation

- Missing exits from stairs leading to an open area outside the building

- Limited number of exits leading to an open area through locked doors without automatic opening during fire in single-story buildings

- Missing other emergency routes—an absence of other staircases or alternative escape possibilities through windows, ladders, etc.

- Insufficient capacity of escape lanes—inwards opening doors narrowing the escape lane and slowing the people's movement speed

These circumstances cause the time for evacuation to be longer, people's safety to be lower and the risk for firefighting brigade to be higher.

The fire development and spreading is a function of time, that is time is crucial for evacuation of people or historic exhibits. Fluent evacuation is conditioned by the number and quality of emergency routes in terms of ventilation, slope, width and number of evacuated persons. Their ventilation and number depend on the building's fire height and the number of evacuated persons. There should be at least two emergency routes available for evacuation in every space; there is significantly better chance of people's survival in spaces directly affected by fire. Evacuated persons can use the emergency route that is less affected by fire.

Staircases are used to evacuate people between floors in buildings. According to STN 730802 and the time required for safe evacuation, staircases can be divided into unprotected, partially protected and protected emergency routes.

Unprotected routes are open staircases and those located within the fire compartment. Partially protected routes are staircases with fire-separating structures preventing the heat and smoke from spreading and those that are not adequately ventilated. Internally enclosed staircases without natural ventilation are the most common. Protected routes are staircases with fire-separating structures preventing the heat and smoke from spreading and natural or artificial ventilation. Routes of type A with natural or forced ventilation with a maximum evacuation time of 6 min are sufficient for historic buildings with the fire height up to 22.5 m. The ventilation requirement is ten times the air change per hour.

6.1 Solution example of a model building's restoration in terms of evacuation

The change of building's functional use and fire load usually results in an increasing number of persons in building compared to the original solution. The evacuation conditions are also changed if the building's fire height is changed, e.g. due to the addition of one or two floors into the attic. Since both cases fundamentally affect the evacuation conditions, it is necessary to check the original emergency routes and modify so that they would be suitable for the new number of evacuated persons or longer emergency route.

Here is the solution example of a model building. The new owner of a manor house changed the building's functional use and fire height by adding a floor into the unused attic space. The manor house is a typical baroque building with a U-shaped ground plan. The manor house had originally three above-ground floors with a mansard roof. The building once served as a residence of a noble family. After restoration, it will serve as a hotel. There are social spaces containing inner halls, smaller salons, restaurants, kitchen and sanitary operational background on the ground floor and first floor. Hotel rooms with technical and operational facilities are located on the upper floors (see **Figure 5**).

Each side wing contains one double-wing staircase that was originally open and classified as unprotected at the time of evacuation. Designed building's alternation by hotel rooms built in the attic changed building's fire height and extended staircases beyond the allowable dimensional limits defined in Table 16 STN 730802. It was necessary to alter existing staircases in the side wings. The staircases on each floor were fire-separated from the other fire-loaded spaces and ventilated through existing windows facing the inner courtyard (see **Figure 5**).

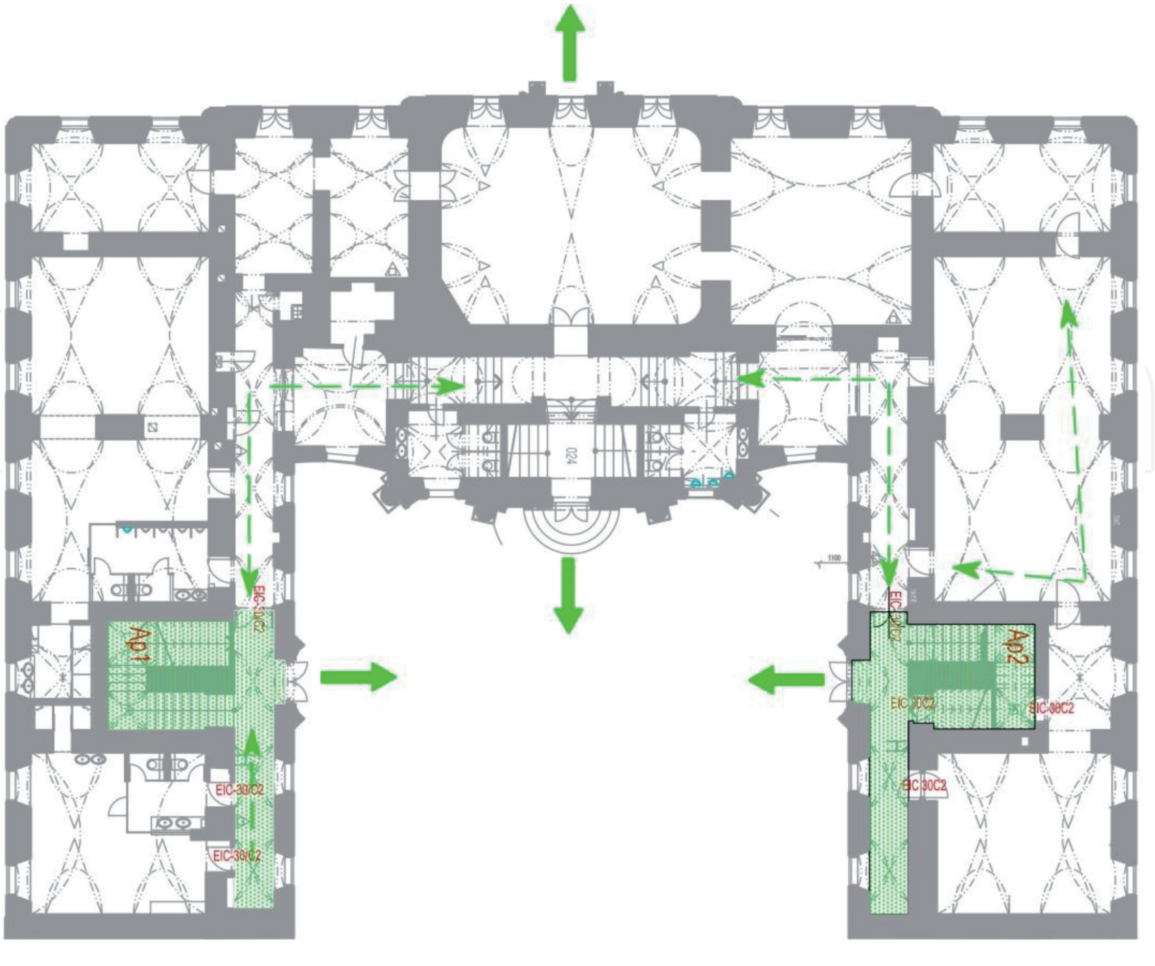

Figure 5.
Emergency routes on the first floor leading to an open area in a model solution of the restored manor house.

7. Conclusions

To achieve higher fire safety in historic buildings whose functional use was changed, it is recommended to optimize the fire risk considering combustibility of building structures and building's fire height. Authors J. Li, H. Li, B. Zhou and X. Wang in their work "Investigation and Statistical Analysis of Fire Load of 83 Historic Buildings in Beijing" analyzed the fire load in timber historic buildings where the primary requirement of the restoration was the optimization of accidental fire load [10].

The building should be divided into fire compartments if it is acceptable in terms of the building conservation. If it is possible, another emergency route with direct ventilation should be created. This route would also serve for firefighting intervention. The large roof spaces should be divided into smaller units using fire-separating walls overlapping the roof by at least 300 mm. An accidental fire loads should be excluded from the attic space. All attic entrances should be provided with self-closing fire doors. Interventions into the original floors should be reduced.

Hidden cavities in the floors should be analyzed in the project documentation due to the load-bearing capacity during the fire intervention as well as in terms of the occurrence of hidden fire caused by short circuits in electrical installations. All cable entries, pipes and anchoring of heavy chandeliers through ceilings should be carefully fire-sealed. The copper roofing on wooden decking or wooden shingles should be replaced with non-combustible roofing made of burnt tiles or slate—see an example of the castle of Krásna Hôrka. The baroque buildings on the Svatá Hora near the town of Příbram in the Czech Republic underwent a similar restoration after a large fire in 1798. The fire affected buildings' wooden roofs as in Krásna Hôrka. The original wooden shingles were replaced by ceramic tiles after fire. The roof spaces in buildings of significant historic importance should be equipped with an automatic fire alarm system, ideally supplemented with an automatic fire extinguishing system. An example of such solution is the protection of the supporting truss members in St. Vitus Cathedral in Prague, Czech Republic. There is an electrical fire alarm and automatic sprinkler fire extinguishing system installed in its roof space.

The spaces containing visible combustible load-bearing and fire-separating structures should be equipped with an automatic fire alarm system. Water sources that can be used for fire extinguishing should be sufficient and located near the building. Accessibility of water sources is often complicated in historic buildings. One of the possibilities is the use of water tanks with 10 m^3 capacity equipped with a 50-m-long fire hose [11].

Access roads should be verified and optimized within natural possibilities. It is important for the building's operation and its fire safety to have functional firefighting equipment and fire-trained staff so that the risks associated with building's restoration and maintenance can be minimized [12–14].

The current fire documentation should be elaborated and updated so as to provide sufficient information on the evacuation plans for persons and exhibits, building's structural design, firefighting water sources and technical condition of access and emergency roads.

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